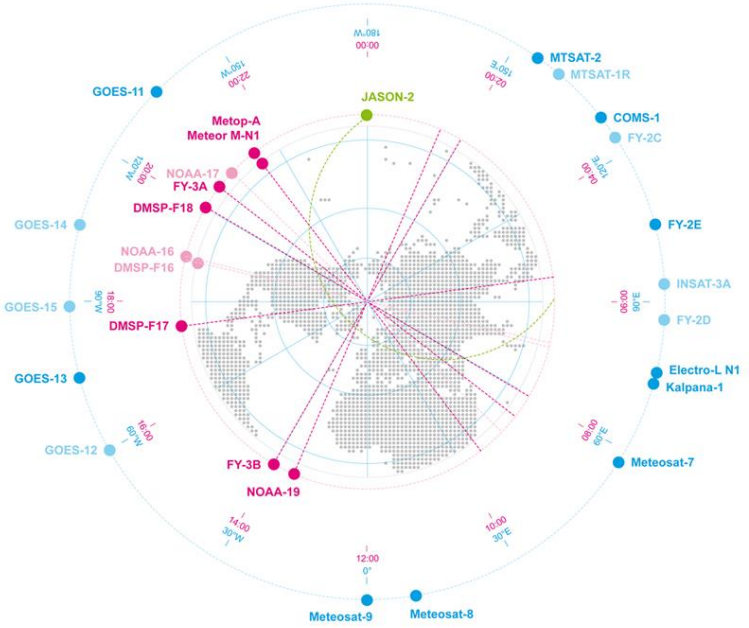

NASA High Resolution Infrared Spectroscopy

Presented to CGMS-48 Plenary Session, HSIR Observations, Agenda 4.2

Presenter: Jack Kaye, NASA Headquarters

Report prepared based on inputs from numerous colleagues at NASA HQ, NASA Centers, and the broader research community

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Presentation Outline

- Current NASA Infrared systems
  - Space-borne
    - Atmospheric Infrared Sounder (AIRS)
    - Tropospheric Emission Spectrometer (TES)
    - Cross-track Infrared Sounder (CrIS)
  - Airborne
    - Hyperspectral Thermal Emission Spectrometer (HyTES)
    - Scanning High-Resolution Interferometer Sounder (S-HIS)
    - NPOESS Airborne Sounder Testbed - Interferometer (NAST-I)
  - Advancements in Small satellite technology
    - Compact Infrared Radiometer in Space (CIRiS)
    - Hyperspectral Thermal Imager (HyTI)
- Future NASA Infrared systems – 2017 Decadal Survey
  - Designated Observables Architecture Studies
  - Decadal Survey Incubation Program
- Concluding Remarks

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Atmospheric Infrared Sounder (AIRS) - Introduction

- **Sun-synchronous** onboard **Aqua**
- **Launched**: 2002
- **Overpass time**: 13:30 ascending
- **Coverage**: Global every 16 days
- **Nadir resolution**: 13.5 km diameter
- **Swath width**: 1650 km

Instrument contractor: Lockheed Martin Infrared Imaging Systems (Lexington, MA)
Spectral coverage & resolution: 2378 channels 3.75 µm to 15.4 µm
Optical design: Grating Spectrometer
Power: 256 Watts
Mass: 166 kilograms

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Tropospheric Emission Spectrometer (TES) - Introduction

- **Sun-synchronous** onboard **Aura**
- **Launched**: 2004
- **Overpass time**: 13:45 ascending
- **Coverage**: Global every 16 days
- **Nadir resolution**: 0.53 x 5.3 km
- **Swath width**: 5.3 x 8.5 km

Decommissioned in 2018

Instrument contractor: Northrop Grumman
Spectral coverage & resolution: channels 3.3 µm to 15.4 µm @ 0.1 cm^{-1} (nadir) and 0.025 cm^{-1} (limb)
Optical design: Fourier Transform Spectrometer (FTS)
Power: 334 Watts
Mass: 385 kilograms

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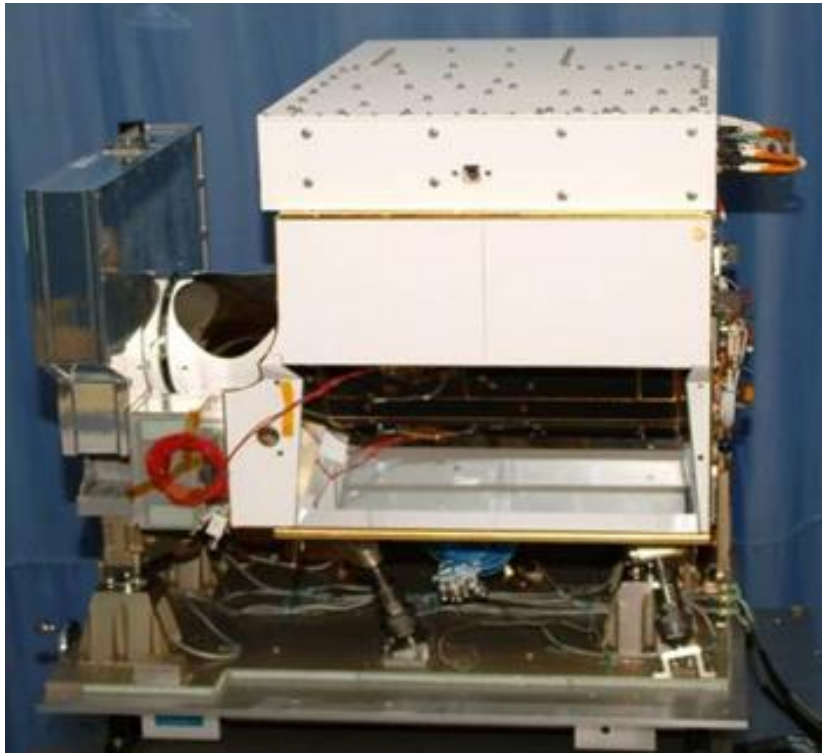
Cross-track Infrared Sounder (CrIS) - Introduction



- **Sun-synchronous** onboard Suomi NPP
- **Launch**: 2011
- **Overpass time**: 13:30 LT, 01:30 LT
- **Coverage**: Near-global, twice a day
- **Nadir resolution**: 14 km
- **Swath width**: 2200 km

Instrument Contractor: Harris Corporation, Fort Wayne, Indiana)
Spectral coverage & resolution: 1305 spectral channels from 3.92 µm to 15.38 µm
Optical Design: Fourier Transform Spectrometer
Power: 245 Watts
Mass: 175 kilograms

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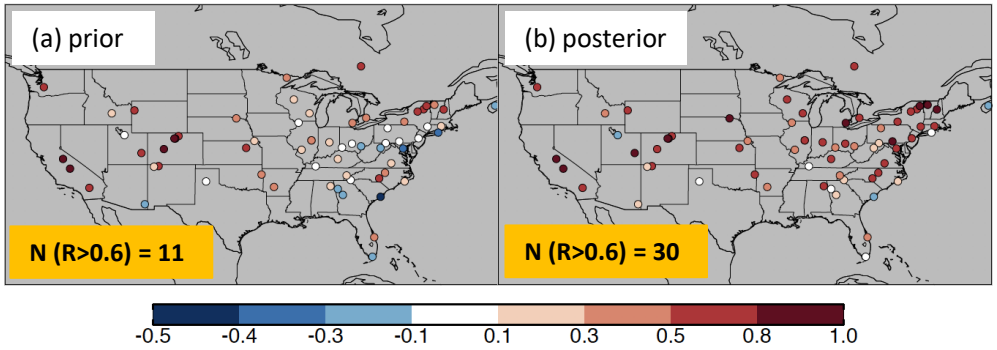
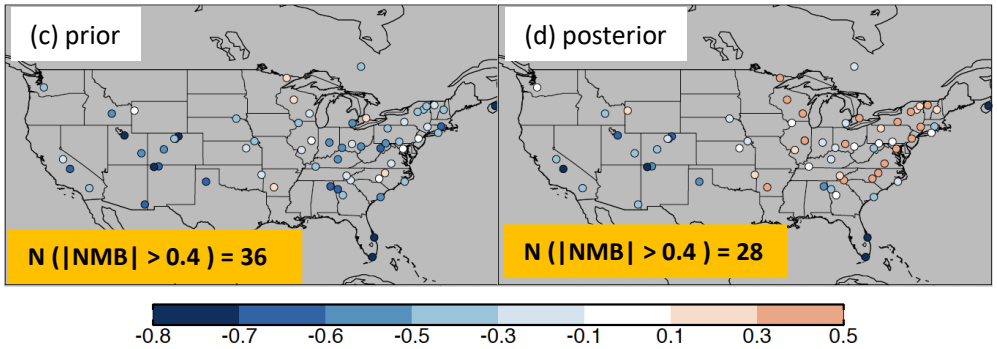
Cross-track Infrared Sounder (CrIS) – Research Results

CrIS-derived NH_3 emissions improved agreement between GEOS-Chem and in-situ measurements

Correlation with surface observation (AMoN)

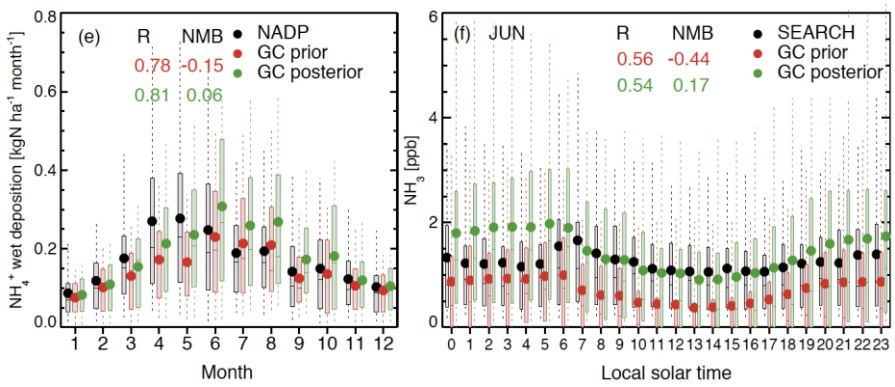


Normalized mean bias (NMB) compared to surface obs (AMoN)



CrIS-derived NH_3 emission enable GC to better reproduce seasonal variability and magnitude of AMoN NH_3 at most sites

Evaluation with wet deposition (left) and hourly observation from SEARCH (right)



CrIS-derived NH_3 emissions enable GC to better reproduce domain averages of hourly South Eastern Aerosol Research and Characterization Network (SEARCH) NH_3 concentrations and monthly measurements of NH_4^+ wet deposition from the NADP network

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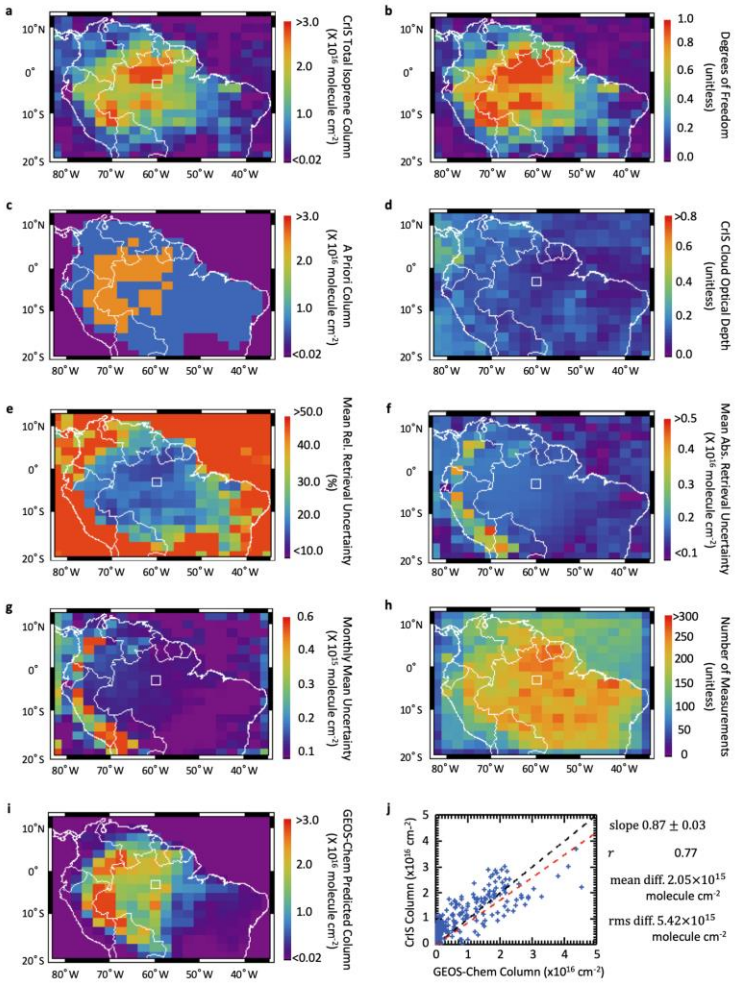
Cross-track Infrared Sounder (CrIS) – Research Results

Comparison of retrieval of isoprene from satellite-based infrared measurements with model estimates



Science Questions: Is it feasible to conduct isoprene (C_5H_8) measurements directly from an existing thermal infrared space-borne instrument? Can we combine space-based measurements of C_5H_8 and formaldehyde (CH_2O) to constrain atmospheric oxidation over C_5H_8 source regions?

Data: Retrieved C_5H_8 columns using Suomi-NPP CrIS measurements. Evaluated using the Gulfstream-1 research aircraft in-situ measurements and GEOS-Chem model. Also, HCHO columns taken from OMI operational L2 products.

Results: This work reveals that the C_5H_8 spectral signatures are detectable from space using the satellite-borne CrIS instrument. Also, quantitatively accounts for spectral interferences and develops a full physics algorithm that quantifies C_5H_8 abundances from these spectral features over Amazonia.

Significance: The discovery of directly space-based C_5H_8 observations, using a full physics algorithm, reveals and accounts for a suite of spectral interreferences over land the ocean scenes, and serve as unambiguous constraints for atmospheric oxidation over C_5H_8 source regions. *This study helps define future missions for quantitatively assessing the impacts of isoprene on air quality and climate.*

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Fu, D., Millet , D.B., Wells, K.C., Payne , V. H., Yu, S., Guenther, A., Eldering A. (2019). Direct retrieval of isoprene from satellite-based infrared measurements. Nature Communication, doi: 10.1038/s41467-019-11835-0.

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Hyperspectral Thermal Emission Spectrometer (HyTES) is an airborne imaging spectrometer with 256 spectral channels between 7.5 and 12 micrometers in the thermal infrared part of the electromagnetic spectrum. HyTES incorporates several new technologies including a Dyson spectrometer, long, straight slit, curved diffraction grating and Quantum Well Infrared Photodetector (QWIP).

Instrument Characteristic	HyTES
Mass (Scanhead)	12kg
Power	400W
Volume	1m x 0.5m (cylinder)
Number of pixels x track	512
Number of bands	256
Spectral Range	7.5 - 12 µm
Spectral Sampling Interval	4.5µm/256, i.e. 17 nm
Frame speed	35 or 22 fps
Integration time (1 scanline)	28 or 45 ms

ER2 Aircraft	
Pixel Size	50 m
Airspeed	410kts
Ceiling	70,000ft
Duration	8 hrs./3,800mi (max. flight altitude)
Electric	28V DC and 400hz. AC
Seats	1 crew

Twin-Otter Aircraft	
Range	2,000 Nmi
Airspeed	65kts
Max Altitude	25,000ft
Duration	5 hours (payload/weather dependent)
Power	5600W (200A MOD) or 8400W (300A MOD)
Onboard Operators	9

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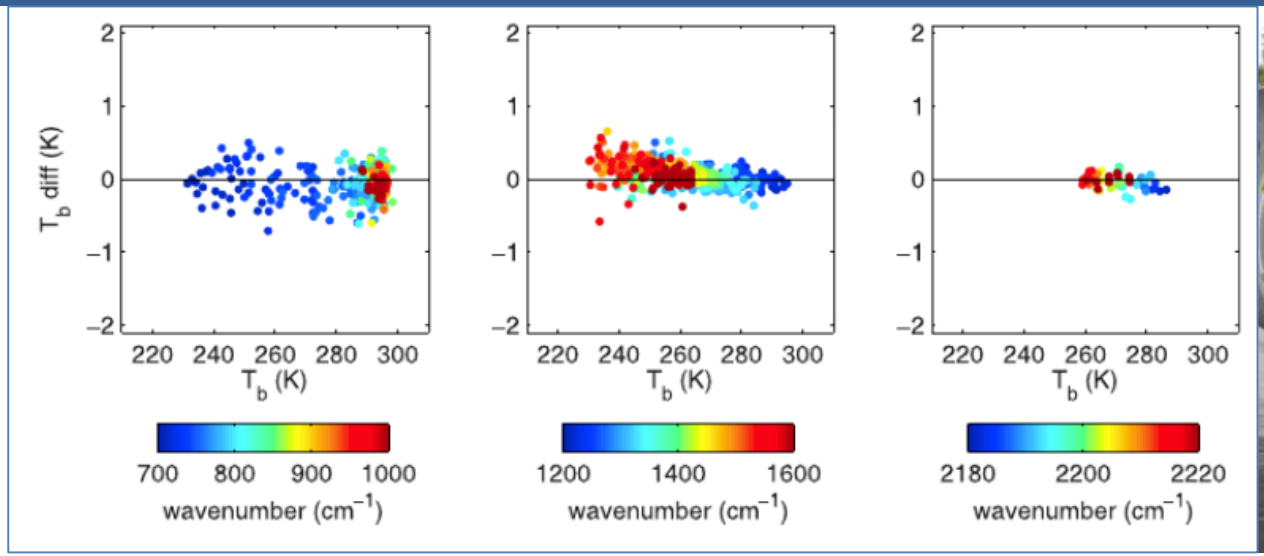
Scanning High-Resolution Interferometer Sounder (S-HIS) is a scanning interferometer which measures emitted thermal radiation at high spectral resolution between 3.3 and 18 microns. The measured emitted radiance is used to obtain temperature and water vapor profiles of the Earth's atmosphere in clear-sky conditions. S-HIS produces sounding data with 2-kilometer resolution (at nadir) across a 40-kilometer ground swath from a nominal altitude of 20 kilometers onboard a NASA ER-2 or Global Hawk.



Brightness temperature differences (AIRS minus Scanning-HIS) shown as a function of AIRS scene brightness temperature. The differences are color coded according to the AIRS channel frequencies for the (left) longwave, (middle) mid wave, and (right) shortwave spectral regions (Tobin et al., 2006)

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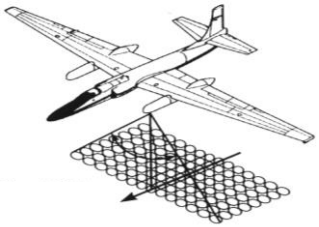
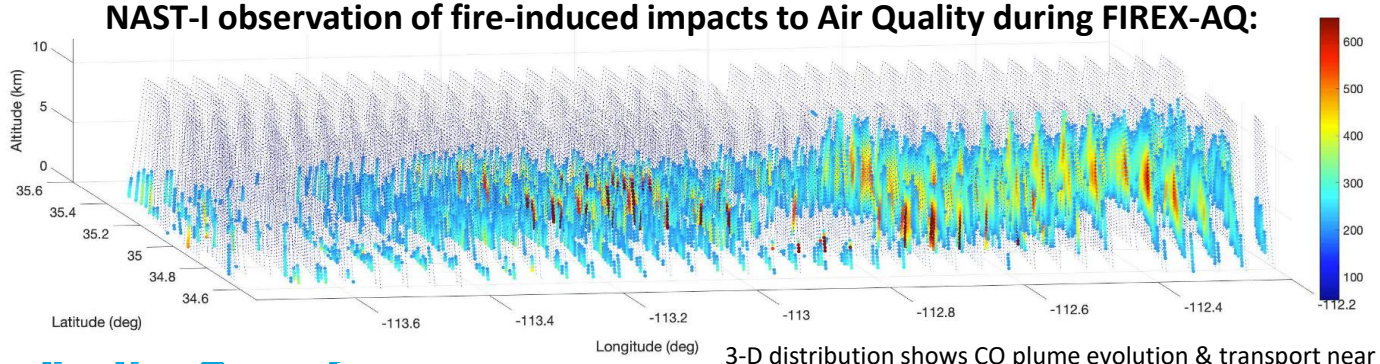
The **National Airborne Sounder Testbed-Interferometer (NAST-I)** is a high spectral (0.25 cm^{-1}) and spatial resolution (130 m linear resolution per km of aircraft flight altitude, at nadir) cross-track scanning (2.3 km ground swath width per km of aircraft flight altitude) interferometer sounding system. Developed to be flown on high-altitude aircraft, the instrument provides infrared spectral radiance (between 3.5 - 16 μ), along with temperature, humidity, trace species, cloud, and surface property soundings at high spectral, spatial, and temporal resolutions. The NAST-I instrument has flown numerous science missions on the NASA ER-2, WB-57, and Proteus aircraft, and the team has evaluated requirements to become operational on the DC-8. Most recently it was part of the ER-2 science payload for the FIREX-AQ campaign (August 2019).

- ✓**Airborne science**
- ✓**Validation tool**
- ✓**Risk mitigation**
- ✓**Engineering testbed**

Data Products: Infrared spectral radiance; profiles / information on atmospheric state & composition, surface and cloud properties.



NAST-I observation of fire-induced impacts to Air Quality during FIREX-AQ:



CO plume (ppb) from Sheridan fire (8/21/2019).

3-D distribution shows CO plume evolution & transport near the fire ground site location (~ 34.8ºN, 112.8ºW), as observed by the high-resolution passive NAST-I interferometer.

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Advancements in Smallsat Technology (1)

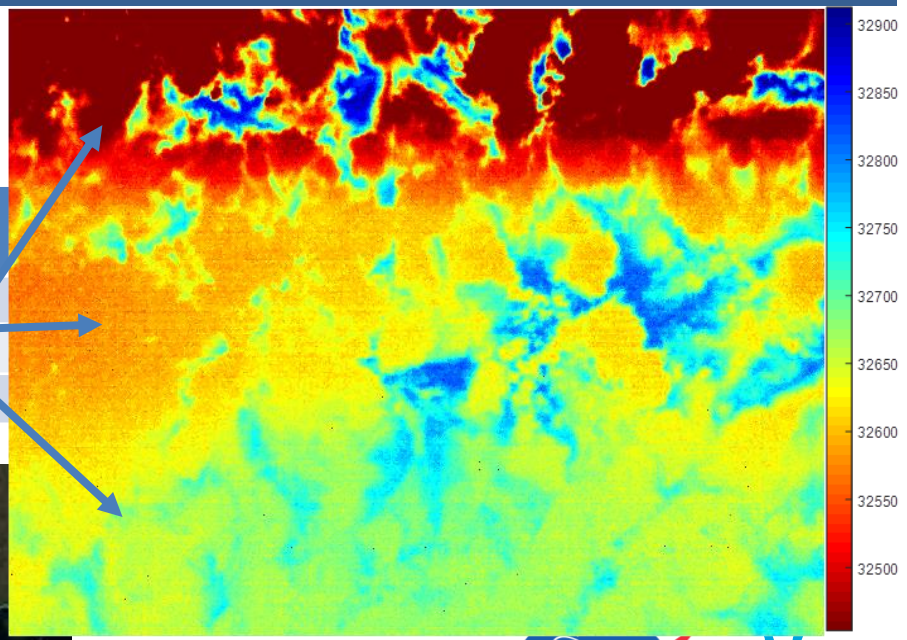
Compact Infrared Radiometer in Space (CIRiS) is a 6U CubeSat, which was selected to validate an uncooled infrared radiometer using carbon nanotubes for on-orbit calibration. CIRiS is collecting highly calibrated images of land and ocean surfaces without active cooling for evapotranspiration, land surface and sea surface measurements.

CIRiS is validating an uncooled microbolometer focal plane assembly and flat-panel carbon nanotube calibration sources. A constellation of these CubeSats could provide highly calibrated infrared imagery with short revisit times and high spatial resolution (<< 1 km) to measure evapotranspiration and land and sea surface temperatures.

Deployed from the ISS on 02/01/20, CIRiS acquired its first Earth images while passing over the South Indian Ocean off the southern coast of Australia on June 17, 2020. On the right is the first light image without calibration showing the three infrared bands CIRiS captured. Data from these three bands will be used to compute temperature, which in turn can be used for evapo-transpiration estimation.

PI: David Osterman/Ball Aerospace

Band	FWHM wavelengths Lower, upper
1	7.40 um, 13.72 um
2	9.85 um, 11.35 um
3	11.77 um, 12.60 um



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Advancements in Smallsat Technology (2)

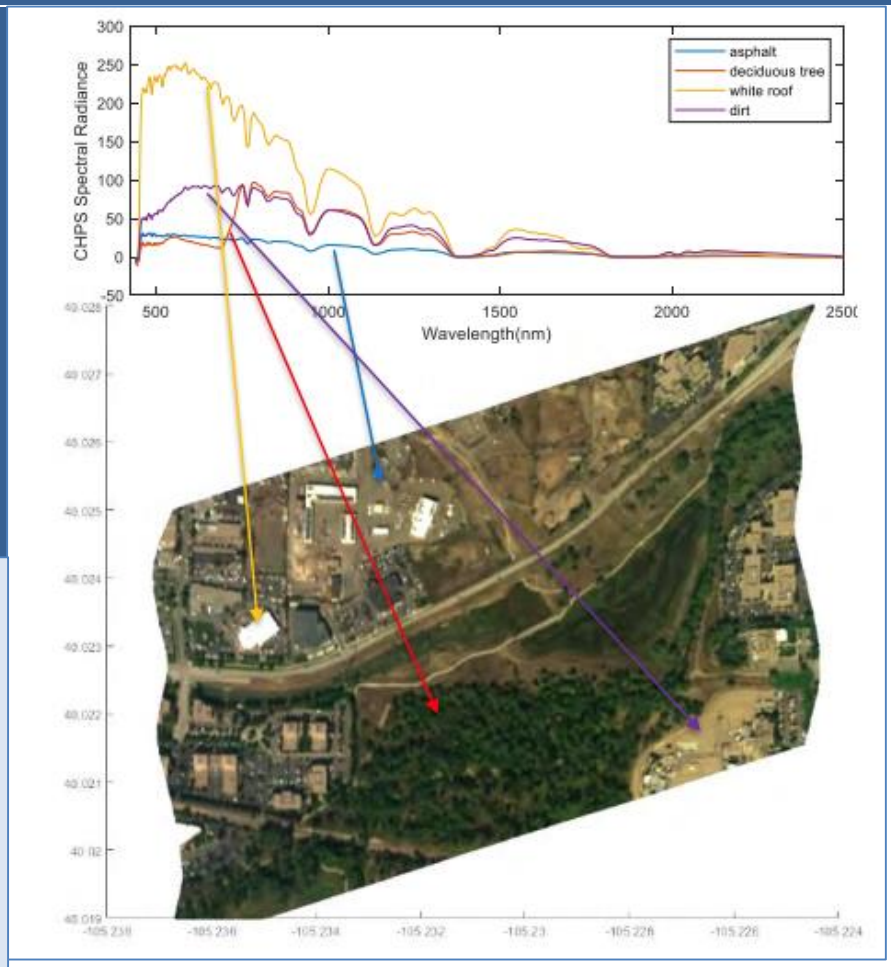
Compact Hyperspectral Prism Spectrometer (CHPS) for Sustainable Land Imaging is an F/3.0 pushbroom system with a 20º Field of View capable of acquiring images in the 400 – 2500 nm range at a spectral resolution of 1.3 to 13 nm/pixel.

The instrument has the potential to provide an order of magnitude reduction in mass and two orders of magnitude reduction in volume compared to the Operational Land Imager (OLI) aboard Landsat-8.

Three airborne field campaigns have been conducted including an engineering flight campaign in March-April of 2019, a science campaign in June-July of 2019, and a science campaign in July 2020.

The image at the right shows hyperspectral data acquired during the July 2019 airborne science campaign over the Boulder Greenway in Colorado.

PI: Tom Kampe/Ball Aerospace



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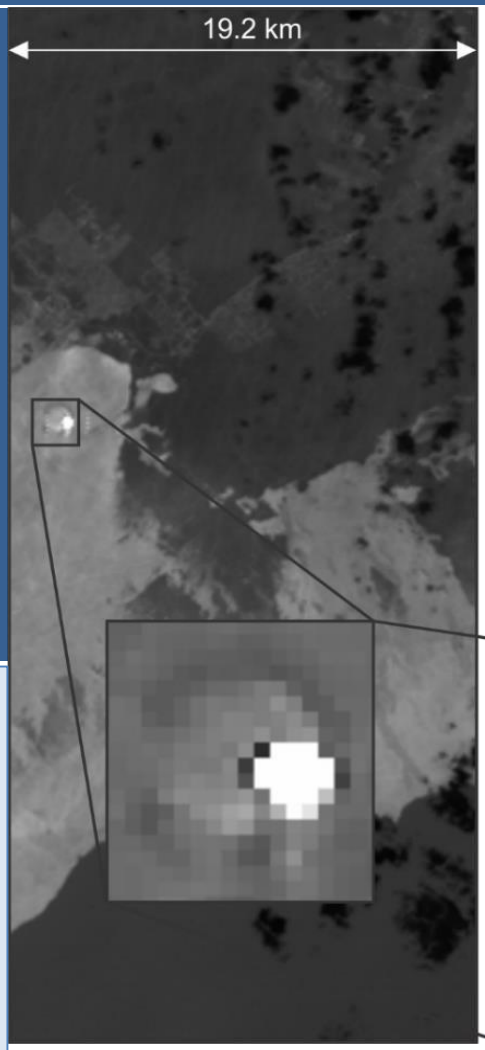
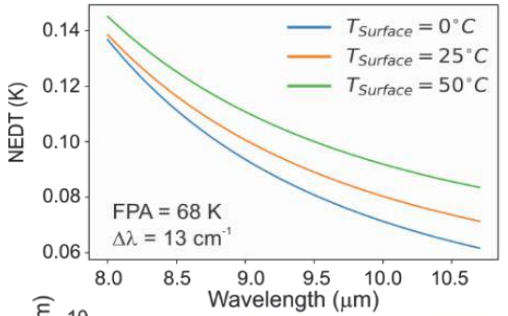
Advancements in Smallsat Technology (3)

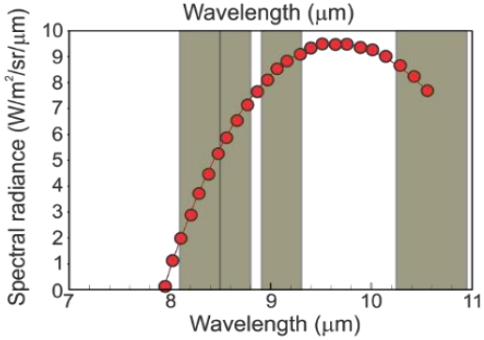
The Hyperspectral Thermal Imager (HyTI) mission will demonstrate how high spectral and spatial long-wave infrared image data can be acquired from a 6U CubeSat platform. HyTI will use a spatially modulated interferometric imaging technique to produce spectro-radiometrically calibrated image cubes with 25 channels between 8-10.7 µm at a ground sample distance of approximately 70 m. It will acquire images at a 19 km wide image swath.

The images to the right (CW starting with longest image): infrared data from the Kilauea volcano resampled to the expected HyTI resolution; instrument's designed spectral band with expected sensor response; and a visible image of Kilauea.

PI: Rob Wright/Univ. Hawaii







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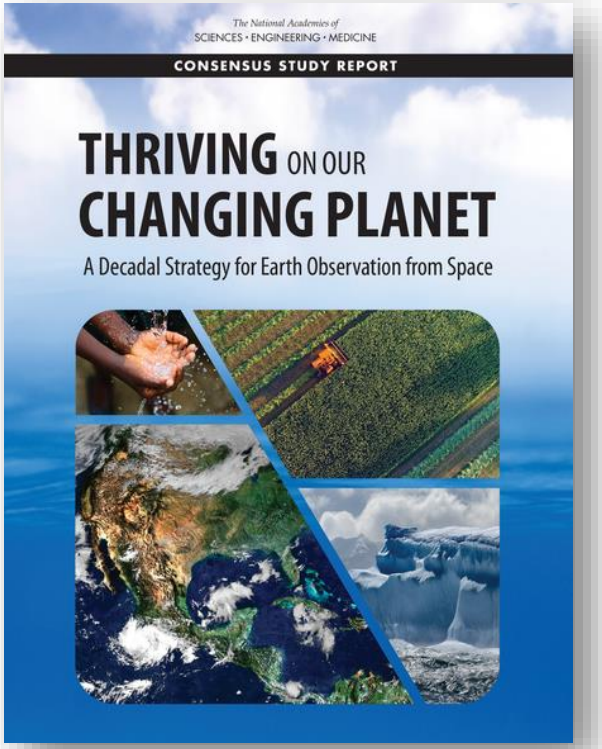
2017 Earth Science Decadal Survey - Overview

Overview

NASA and the U.S. Government rely on the scientific community to identify and prioritize leading-edge scientific questions and the observations required to answer them. In response to their request, the National Academies of Sciences, Engineering, and Medicine appointed an ad hoc committee – Committee on Earth Science and Applications from Space (ESAS) – to carry out a decadal survey of Earth Science and Applications. In 2018, ESAS released their report that provides recommendations from the environmental monitoring, Earth science research, and applications communities for an integrated and sustainable approach to the conduct of the U.S. government's civilian space-based Earth-system science programs.

Recommended Elements of Strategic Framework for the Next Decade

- Commit to sustained science and applications
- Embrace innovative methodologies for integrated science/applications
- Amplify the cross-benefit of science and applications
- Leverage external resources and partnerships
- Institutionalize programmatic agility and balance
- Exploit external trends in technology and user needs
- Expand use of competition
- Pursue ambitious science, despite constraint



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2017 Decadal Survey Recommendations

Program of Record. The series of existing or previously planned observations, which **should be completed as planned**. Execution of the ESAS 2017 recommendation requires that the total cost to NASA of the Program of Record *flight missions from FY18-FY27 be capped at $3.6B.*

- ***Designated.*** A new program element for ESAS-designated cost-capped medium- and large-size missions to address ***observables essential to the overall program*** and that are outside the scope of other opportunities in many cases. Can be competed, at NASA discretion.
- ***Earth System Explorer.*** A new program element involving competitive opportunities for medium-size instruments and missions serving specified ESAS-priority observations. ***Promotes competition among priorities.***
- ***Incubation.*** A new program element, focused on investment for priority observation opportunities needing advancement prior to cost-effective implementation, including an Innovation Fund to respond to emerging needs. ***Investment in innovation for the future.***
- ***Venture.*** Earth Venture program element, as recommended in ESAS 2007 with the addition of a new Venture-Continuity component to provide ***opportunity for low-cost sustained observations.***

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In early 2018, NASA Earth Science Division initiated 4 multi-center **Decadal Survey Designated Observable Mission Architecture Study Teams** to explore implementation options for observing systems to address the **Five Targeted Observables**. One each for Aerosols (A), Clouds, Convection and Precipitation (CCP); Mass Change (MC); Surface Biology and Geology (SBG); and Surface Deformation and Change (SDC).

- Each team has drafted a Science and Applications Traceability Matrix (SATM) as part of an overall value framework against which to assess potential architectures.
- The teams have been challenged to broaden the trade space of potential solutions beyond single-satellite concepts, and to consider options that included multiple satellites in constellation, commercial satellite data, and international partnerships. The team will present the highest ranked solutions to ESD for consideration.
- After an internal evaluation, ESD will select an architecture and the study team will work to develop the concept further, in preparation for a Mission Concept Review (MCR) and formal project initiation.

TABLE S.2 Observing System Priorities (see note following table for description)

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated
Aerosols	*Aerosol properties, aerosol vertical profiles, and cloud properties* to understand their effects on climate and air quality	Backscatter lidar and multichannel/multiangle/ polarization imaging radiometer flown together on the same platform	X
Clouds, Convection, and Precipitation	*Coupled cloud-precipitation state and dynamics* for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Dual-frequency radar, with multifrequency passive microwave and sub-mm radiometer	X
Mass Change	*Large-scale Earth dynamics* measured by the changing mass distribution within and between the Earth's atmosphere, oceans, groundwater, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X
Surface Biology and Geology	*Earth surface geology and biology,* ground/water temperature, snow reflectivity, active geologic processes, vegetation traits, and algal biomass	Hyperspectral imagery in the visible and shortwave infrared (IR), multi- or hyperspectral imagery in the thermal IR	X
Surface Deformation and Change	*Earth surface dynamics* from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X

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Launched in 2019, the goal of the **Decadal Survey Incubation Program** is to accelerate the readiness of cost-effective flight implementations of **Planetary Boundary Layer (PBL)** and **Surface Topography and Vegetation (STV) Targeted Observables**. It supports maturation of mission, instrument, technology, and/or measurement concepts to address specific high priority science research needs. While overall management of the program was assigned to ESTO, it is closely coordinated with the NASA ESD's Research and Analysis (R&A) program. Since its inception, two study teams have been selected, one each for PBL and STV, and are in the process of developing a white paper that will inform strategy and decisions related to release of research solicitation in 2021. In addition to the work of the study teams, several ongoing activities funded by R&A and ESTO are aligned with and compliment the work of PBL and STV teams.

TABLE S.2 Continued

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Planetary Boundary Layer	*Diurnal 3D PBL thermodynamic properties and 2D PBL structure* to understand the impact of PBL processes on weather and air quality through high vertical and temporal profiling of PBL temperature, moisture, and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar* for PBL height			X
Surface Topography and Vegetation	*High-resolution global topography*, including bare surface land topography, ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar*			X